

TIMING EFFECTS OF CARBON MITIGATION AND SOLAR RADIATION MANAGEMENT POLICIES

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SUMMARY

We study timing effects of carbon mitigation and solar radiation management (SRM) policies by introducing a general equilibrium framework with correlated pollutants. We show that first-mover advantage exists in deciding both carbon emissions quotas and SRM levels, and levels of national carbon quotas, sulfur quotas and SRM are positively correlated with each other. Moreover, we demonstrate that national sensitivities to acid rain damages play important roles in governments' environmental policies. With an example, we illustrate that if international equity is considered, then governments could be willing to choose SRM levels before carbon quotas since it yields higher payoffs and less acid rain and droughts damages. This timing was neglected by all previous theoretical economic models on geoengineering.

CHAPTER I

INTRODUCTION

Over the years, people have been trying to relieve global warming by mitigating emissions of greenhouse gases (GHG). However, so far, attempts in that direction have been grossly unsuccessful. Therefore, artificial ways to modify the climate, or so-called geo-engineering, have been rekindled by scientists. Among all, solar radiation management (SRM) is one of the most promising technologies. It injects sulfate aerosols into the stratosphere, which backscatter part of the solar radiation striking the earth, thus reducing the temperature. They are also expected to stop the melting of sea ice and land-based glaciers, slow sea level rise and increase the terrestrial carbon sink. However, like any other technologies, it is a double-edged sword as well. Problems such as droughts, ozone depletion, less sunlight for solar power and less blue skies might emerge.^[5] Our paper considers drought as an example of the damage caused by SRM.

Moreover, in contrast to carbon abatement, geoengineering technologies are inexpensive and can be undertaken by a single nation, unilaterally.^[1] This enables nations to move strategically in making abatement and SRM policies, which causes a “moral hazard” concern that some countries may emit more by using SRM as the last resort. Literatures in economics have discussed from different angles possible mitigation reactions in view of future implementation of geoengineering technologies. Moreno-Cruz (2011)^[4] considers the strategic interactions between both symmetric and asymmetric

countries. For similar nations, he finds that the prospect of SRM will create greater incentives for free-riding on carbon mitigation, while for asymmetric ones, it can induce inefficiently high levels of mitigation. Urpelainen (2012)^[6] also examines the strategic logic of unilateral geoengineering. He finds that if geoengineering produces severe negative externalities, it may spur deeper emissions reductions in the present. If the externalities are not overly severe, unrestricted geoengineering can be globally beneficial, which concludes from the comparisons of behavior and payoffs to countries with and without the technology. Millard-Ball (2012)^[3] studies this issue by focusing on the formation of a mitigation agreement. He shows that a credible threat of unilateral geoengineering may instead strengthen global abatement and lead to a self-enforcing climate treaty with full participation.

There are at least two common features of those papers. One is that they share a common timing where carbon reductions are prior to geoengineering choices. However, due to the much lower technology cost of geoengineering, it is not impossible that some countries will be more willing to apply climate engineering than carbon mitigation. Hence, those nations may decide SRM levels before carbon emissions levels. The second feature is that none of them has mentioned sulfur dioxide emissions which cause acid rain damages. And yet, in effect, carbon policies should be closely related to sulfur policies. Consider one of the key pollution emitters, the energy industry. As first pointed out by Silva^[2], energy production process generates not only GHG such as carbon dioxide, but also sulfur dioxide. Meanwhile, our model results confirm that national carbon quota levels are affected by domestic sensitivities to acid rain damage as well.

Our paper takes into account those two missing points in the literature. We first establish a general equilibrium framework with correlated pollutants, CO_2 and SO_2 . We assume that one unit of energy production emits one unit of CO_2 and one unit of SO_2 . Governments decide not only amounts of carbon emissions and SRM, but also those of sulfur emissions. Note that by analyzing the general equilibrium, our model is more realistic than current ones in one additional dimension as interactions in the whole economy are considered. Next, we study and compare six games with different timings in deciding carbon quotas and SRM levels. Specifically, we divide the games into three categories: carbon quotas are chosen first, SRM levels are chosen first and carbon and SRM levels are chosen simultaneously. For the first two categories, we further distinguish each one by the fact that if or not there exists national leadership in making the first-stage decisions. For the third category, we examine both uncoordinated and coordinated games. We carry out our analysis by first assuming general functional forms and then looking at a specific example.

Results of the general model exhibit positive correlations among levels of sulfur permits, carbon permits and SRM. This implies that expectation of future SRM technology does increase current carbon emissions, confirming the public's moral hazard concern. Meanwhile, we demonstrate that there exist first-mover advantages in both carbon quotas and SRM decisions. With the example, we verify that sulfur emissions levels are linked to carbon emissions and SRM levels through both energy production and national sensitivities to acid rain damages. In general, the more prone to acid rain one nation is, the less carbon and sulfur pollutions it will produce, and the less SRM is implemented. But all results are the opposite if the other nation suffers

more from acid rain. Furthermore, our ranking of national payoffs shows that indeed, countries may be more willing to determine SRM levels before carbon quotas as those games generally yield higher utility for both nations. The ranking of environmental damages presents the same tendency when nations care more about acid rain and droughts than global warming.

The remainder of the paper is organized as follows. Chapter 2 introduces the general model. Chapter 3 presents an example with specific functional forms. Chapter 4 concludes.

CHAPTER II

MODEL

2.1 *Setting*

Consider a global economy consisting of two nations, indexed by j , $j = 1, 2$. For simplicity, we normalize the population of each nation, letting it be equal to 1. Both nations suffer from droughts caused by solar radiation management (SRM), global warming caused by emissions of carbon dioxide and acid rain caused by emissions of sulfur dioxide. Carbon dioxide and sulfur dioxide emissions are by-products of energy production in each nation.

Let $H^T(C, M)$ denote the harm function associated with global warming in each nation, where $C = \sum_{j=1}^2 C_j$ and $M = \sum_{j=1}^2 M_j$ are global levels of carbon dioxide and SRM, respectively. Let $H_j^A(\theta_j, S_j)$ be the harm function of acid rain deposition in nation j , where S_j is the level of sulfur dioxide in nation j and $\theta_j \in (1, 2)$, $\forall j = 1, 2$ denotes its sensitivity to acid rain damage. The drought caused by SRM in each nation is represented by $H^D(M)$. Assume that all harm functions are quadratic. Moreover, H^T increases in C and decreases in M (i.e., SRM is a public good). H_j^A and H^D are increasing functions. nation j 's total level of environmental damages is

$$H_j = H_j(C, M, S_j) = H^T(C, M) + H_j^A(\theta_j, S_j) + H^D(M). \quad (2.1)$$

A representative consumer in nation j consumes x_j units of composite good (numeraire), e_j units of energy and is harmed by H_j units of environmental damages.

Let $u_j(x_j, e_j, H_j)$ denote consumer j 's utility function. Assume that u_j is quasi-linear (linear in x_j), strictly concave in e_j and increasing in consumption of both composite and energy goods. More precisely, we assume that $u_j(x_j, e_j, H_j) = x_j + f_j(e_j) - H_j$, where $f_j(0) = 0$, $f_j'(0) > f_j'(w_j) > 0$, $f_j'' < 0$ for all $e_j > 0$ and $f_j''' = 0$ for all $e_j \geq 0$.

The consumer's income is denoted w_j :

$$w_j = \overline{x_j} + p_{C_j}Q_{C_j} + p_{S_j}Q_{S_j} + \pi_j - K_j^M, \quad (2.2)$$

where $\overline{x_j}$ is an initial endowment of the numeraire good. Each consumer is assigned carbon and sulfur quotas by his/her national government and receives revenue, $p_{C_j}Q_{C_j} + p_{S_j}Q_{S_j}$ from sales of the permits to the domestic energy industry (where p_{C_j} and p_{S_j} are prices of carbon and sulfur permits in nation j , respectively). He/she also earns profits of the energy industry in nation j , π_j , and pays a tax equal to the public expenditure on SRM in nation j , K_j^M . The government of nation j makes decisions on national quantities of carbon and sulfur quotas to be issued, Q_{C_j} and Q_{S_j} and the level of SRM, M_j , to be provided. For future reference, note that $C \equiv Q_{C_1} + Q_{C_2} \equiv Q_C$, $M_1 + M_2 \equiv M$ and $S_j = Q_{S_j}$, $j = 1, 2$. Throughout, we assume that markets are competitive, with both consumers and energy firms taking prices as given. Consumers also take their incomes and the levels of pollution damages as given.

2.2 *General Equilibrium Framework with Correlated Pollutants*

The goal of consumer j is to maximize $u_j(x_j, e_j, H_j) = x_j + f_j(e_j) - H_j$ by choosing non-negative $\{x_j, e_j\}$, subject to $x_j + p_{e_j}e_j = w_j$, where p_{e_j} is nation j 's energy price. This is equivalent to choosing non-negative e_j to maximize $f_j(e_j) - p_{e_j}e_j$. Assuming interior solutions, the first-order condition is:

$$f'_j(e_j) - p_{e_j} = 0. \quad (2.3)$$

Condition (2.3) informs us that the optimal level of energy to be consumed is the one at which the marginal utility from energy equates the price of energy. Since the second-order condition is $f''_j(e_j) < 0$, the solution to the consumer's maximization problem is unique. Equation (2.3) implicitly defines $e_j(p_{e_j})$, consumer j 's energy demand. The demand for the numeraire good is $x_j(p_{e_j}, w_j) = w_j - p_{e_j}e_j(p_{e_j})$. Thus, $v_j(p_{e_j}, w_j, H_j) = w_j - p_{e_j}e_j(p_{e_j}) + f_j(e_j(p_{e_j})) - H_j$ is consumer j 's indirect utility function.

In nation j , the energy firm's profit function is

$$\pi_j(E_j, R_{C_j}, R_{S_j}) = p_{e_j}E_j - p_{C_j}(E_j - R_{C_j}) - p_{S_j}(E_j - R_{S_j}) - K_j^E(E_j) - K_j^C(R_{C_j}) - K_j^S(R_{S_j}),$$

where E_j , R_{C_j} , R_{S_j} are levels of energy production, carbon dioxide reduction and sulfur reduction, respectively. K_j^E , K_j^C , K_j^S are the corresponding costs of energy production and pollution abatement, and are all increasing and strictly convex. Each firm chooses non-negative $\{E_j, R_{C_j}, R_{S_j}\}$ to maximize π_j , taking all prices as given.

The first-order conditions for interior solutions are as follows:

$$p_{e_j} - p_{C_j} - p_{S_j} - \frac{dK_j^E}{dE_j} = 0, \quad (2.4a)$$

$$p_{C_j} - \frac{dK_j^C}{dC_j} = 0, \quad (2.4b)$$

$$p_{S_j} - \frac{dK_j^S}{dS_j} = 0, \quad (2.4c)$$

Condition (2.4a) informs us that the optimal amount of energy to be produced in a nation should equate the marginal revenue to the sum of marginal production and regulatory costs of energy production. Equation (2.4b) states that the optimal level of carbon abatement should equate the marginal revenue from carbon abatement (i.e., the marginal cost saving in expenditure on carbon permits) to the marginal cost of carbon abatement. Equation (2.4c) is similar; it equates marginal revenue from sulfur abatement to the marginal cost of sulfur abatement.

We have also verified that the Hessian matrix is negative definite, which implies strict concavity of the profit function and ensures a unique solution to the maximization problem. We can, therefore, invoke the implicit function theorem and define the decision variables of the energy industry from equations (2.4a) to (2.4c) as¹ :

$E_j(p_{e_j}, p_{C_j}, p_{S_j})$, $R_{C_j}(p_{C_j})$ and $R_{S_j}(p_{S_j})$ with:

$$\frac{\partial E_j}{\partial p_{e_j}} = -\frac{\partial E_j}{\partial p_{C_j}} = -\frac{\partial E_j}{\partial p_{S_j}} = \frac{1}{d^2 K_j^E / dE_j^2} > 0, \quad (2.5a)$$

$$\frac{dR_{C_j}}{dp_{C_j}} = \frac{1}{d^2 K_j^C / dR_{C_j}^2} = 0, \quad (2.5b)$$

$$\frac{dR_{S_j}}{dp_{S_j}} = \frac{1}{d^2 K_j^S / dR_{S_j}^2} = 0, \quad (2.5c)$$

¹See the derivation in Appendix A.1.

Firm j 's indirect profit function is

$$\begin{aligned}\pi_j(p_{e_j}, p_{C_j}, p_{S_j}) &= E_j(p_{e_j}, p_{C_j}, p_{S_j})[p_{e_j} - p_{C_j} - p_{S_j}] + p_{C_j} R_{C_j}(p_{C_j}) \\ &\quad + p_{S_j} R_{S_j}(p_{S_j}) - K_j^E(E_j(p_{e_j}, p_{C_j}, p_{S_j})) \\ &\quad - K_j^C(R_{C_j}(p_{C_j})) - K_j^S(R_{S_j}(p_{S_j}))\end{aligned}$$

Market-clearing conditions for the national energy market, and carbon and sulfur quota markets, respectively, are as follows:

$$e_j(p_{e_j}) = E_j(p_{e_j}, p_{C_j}, p_{S_j}), \quad (2.6a)$$

$$E_j(p_{e_j}, p_{C_j}, p_{S_j}) - R_{C_j}(p_{C_j}) = Q_{C_j}, \quad (2.6b)$$

$$E_j(p_{e_j}, p_{C_j}, p_{S_j}) - R_{S_j}(p_{S_j}) = Q_{S_j}, \quad (2.6c)$$

Condition (2.6a) informs us that in each nation the demand for energy must be equal to the supply of energy. Condition (2.6b) states that in each nation, the demand for carbon permits must be equal to the supply of carbon permits. Condition (2.6c) is similar to condition (2.6b): the demand for sulfur permits equals the supply of sulfur permits.

Since the Jacobian matrix associated with the system of equations (2.6) is non-singular, we can invoke the implicit function theorem to define the following implicit functions:² $p_{e_j}(Q_{C_j}, Q_{S_j})$, $p_{C_j}(Q_{C_j}, Q_{S_j})$, and $p_{S_j}(Q_{C_j}, Q_{S_j})$. The following results

²See Appendix A.2 for the proof.

can now be obtained:

$$\frac{\partial p_{e_j}}{\partial Q_{C_j}} = - \frac{f_j''(e_j) \left[2 \left(\frac{d^2 K_j^C}{dR_{C_j}^2} \right) + \frac{d^2 K_j^E}{dE_j^2} \right]}{2 \left(\frac{d^2 K_j^E}{dE_j^2} \right)}, \quad (2.7a)$$

$$\frac{\partial p_{C_j}}{\partial Q_{C_j}} = \frac{1}{2} \left(f_j''(e_j) - \frac{d^2 K_j^C}{dR_{C_j}^2} - \frac{d^2 K_j^E}{dE_j^2} \right), \quad (2.7b)$$

$$\frac{\partial p_{S_j}}{\partial Q_{C_j}} = \frac{\frac{d^2 K_j^C}{dR_{C_j}^2} \left(\frac{d^2 K_j^E}{dE_j^2} - 2f_j''(e_j) \right)}{2 \left(\frac{d^2 K_j^E}{dE_j^2} \right)}, \quad (2.7c)$$

$$\frac{\partial p_{e_j}}{\partial Q_{S_j}} = - \frac{f_j''(e_j) \left[2 \left(\frac{d^2 K_j^S}{dR_{S_j}^2} \right) + \frac{d^2 K_j^E}{dE_j^2} \right]}{2 \left(\frac{d^2 K_j^E}{dE_j^2} \right)}, \quad (2.7d)$$

$$\frac{\partial p_{C_j}}{\partial Q_{S_j}} = \frac{1}{2} \left(f_j''(e_j) - \frac{d^2 K_j^S}{dR_{S_j}^2} - \frac{d^2 K_j^E}{dE_j^2} \right), \quad (2.7e)$$

$$\frac{\partial p_{S_j}}{\partial Q_{S_j}} = \frac{\frac{d^2 K_j^S}{dR_{S_j}^2} \left(\frac{d^2 K_j^E}{dE_j^2} - 2f_j''(e_j) \right)}{2 \left(\frac{d^2 K_j^E}{dE_j^2} \right)}, \quad (2.7f)$$

We summarize our findings about the equilibrium price functions in the following proposition.

Proposition 1.

$$\frac{\partial p_{e_j}}{\partial Q_{C_j}} > 0, \frac{\partial p_{C_j}}{\partial Q_{C_j}} < 0, \frac{\partial p_{S_j}}{\partial Q_{S_j}} > 0, \frac{\partial p_{e_j}}{\partial Q_{S_j}} > 0, \frac{\partial p_{C_j}}{\partial Q_{S_j}} > 0, \text{ and } \frac{\partial p_{S_j}}{\partial Q_{S_j}} < 0, \quad \forall j = 1, 2.$$

Proof. See Appendix A.3. □

To illustrate the intuition behind the proposition, let us analyze how prices change when Q_{C_j} changes. If Q_{C_j} increases, p_{C_j} decreases. This is expected since the demand for carbon permits is decreasing in the carbon permit price and the supply of permits is perfectly inelastic. The decreasing in the carbon permit price reduces the firm's marginal regulatory cost, holding all other prices constant, increasing the firm's marginal revenue from energy production. Thus, the firm has an initial incentive to respond by increasing energy production and associated carbon and sulfur emissions, with a subsequent shift in the firm's demand curve for sulfur emission permits to the right. Given an inelastic supply of sulfur permits, the shift in the demand for sulfur permits results in an increase in the price of the sulfur permit. The increase in the price of the sulfur permit more than offsets the decrease in the price of the carbon permit, leading to an overall increase in the marginal regulatory cost. Thus, the firm's energy supply curve shifts in, leading to a contraction in the equilibrium energy level and an increase in the energy price. Therefore, the existence of a limit on the supply of sulfur permits leads to an overall net increase in the cost of producing energy when the supply of carbon permits is expanded. This effect would not be present if there was no regulation on sulfur emissions.

We are now ready to write consumer j 's indirect utility as function of pollution

quotas and SRM provision levels:

$$\begin{aligned}
v_j(Q_{C_j}, Q_{C_{-j}}, Q_{S_j}, M_j, M_{-j}) = & \overline{x_j} + f_j(e_j(p_{e_j}(\cdot))) - K_j^E(E_j(p_{e_j}(\cdot), p_{C_j}(\cdot), p_{S_j}(\cdot))) \\
& - K_j^C(R_{C_j}(p_{C_j}(\cdot))) - K_j^S(R_{S_j}(p_{S_j}(\cdot))) \\
& K_j^M(M_j) - H_j^A(\theta_j, Q_{S_j}) - H^T(Q_C, M) - H^D(M),
\end{aligned} \tag{2.8}$$

where

$$p_{e_j}(\cdot) = p_{e_j}(Q_{C_j}, Q_{S_j}), \quad p_{C_j}(\cdot) = p_{C_j}(Q_{C_j}, Q_{S_j}), \quad p_{S_j}(\cdot) = p_{S_j}(Q_{C_j}, Q_{S_j}),$$

and $M = M_j + M_{-j}$, $j = 1, 2$.

Throughout the paper, we define $-j = 1$ if $j = 2$ and $-j = 2$ if $j = 1$.

2.3 Games on Environmental Policies in the Presence of SRM

We now examine the effects of the timing of environmental policy. We consider sequential policy games in order to compare the effects of committing to a policy of setting the quota on carbon emissions with the effects of committing to a policy of setting the level of SRM to be provided. In all games, we assume that the national governments select their sulfur quotas at the last stage.

We establish two benchmarks under which policy making on carbon quotas and SRM levels occur simultaneously in the first stage of two-stage games: (i) uncoordinated policy making; and (ii) coordinated policy making. Sulfur quotas are chosen simultaneously in the second stage of the game. The benchmarks will enable us to

capture both the effects caused by the timing of policy making and the effects caused by non-cooperative behavior (i.e., departures from socially efficient behavior). The next two sequential games involve simultaneous choices of either (iii) pollution quotas or (iv) SRM levels in the first stage, with simultaneous choices of either SRM (in game (iii)) or pollution quotas (in game (iv)) in the second stage. Thus, unlike the games in which pollution quotas and SRM are chosen simultaneously, games (iii) and (iv) involve three stages, since sulfur quotas are simultaneously chosen in the third stage of the game. The last two sequential games involve four stages. In game (v), nation 1 chooses its pollution quota in the first stage, nation 2 chooses its pollution quota in the second stage, SRM levels are chosen simultaneously in the third stage and sulfur quotas are chosen simultaneously in the fourth stage. In game (vi), nation 1 chooses its SRM level in the first stage, nation 2 chooses its SRM level in the second stage, carbon quotas are chosen simultaneously in the third stage and sulfur quotas are chosen simultaneously in the fourth stage. The equilibrium concept utilized is subgame perfection.

Consider the last stage of any sequential game, namely, the stage in which the nations choose sulfur quotas simultaneously after having observed the other policy choices, $\{Q_{C_j}, Q_{C_{-j}}, M_j, M_{-j}\}$. The optimization problem faced by nation j 's government is to choose non-negative $\{Q_{S_j}\}$ to maximize the national indirect utility function (2.8), taking $Q_{S_{-j}}$ as given. Assuming interior solutions, we obtain the

following first-order condition:³

$$p_{S_j} - \frac{\partial H_j^A}{Q_{S_j}} = 0, \quad \forall j = 1, 2. \quad (2.9)$$

Condition (2.9) informs us that the amount of sulfur quotas should be set at the level that equates the national permit price to the national marginal damage caused by acid rain. Since H_j^A is strictly convex, the sufficient second order is satisfied in each maximization problem. Applying the implicit function theorem to each equation (2.9), we can define the optimal functions $Q_{S_j}(Q_{C_j}; \theta_j)$, $j = 1, 2$. Since neither p_{S_j} or H_j^A depend on $(Q_{C_{-j}}, M_j, M_{-j})$. Differentiation with respect to Q_{C_j} yields

$$\frac{\partial Q_{S_j}}{\partial Q_{C_j}} = \frac{(\partial P_{S_j} / \partial Q_{C_j})}{\left(\partial^2 H_j^A / \partial Q_{S_j}^2 \right) - (\partial P_{S_j} / \partial Q_{S_j})}, \quad j = 1, 2 \quad (2.10)$$

By (1) and strict convexity of H_j^A , we have $\partial Q_{S_j} / \partial Q_{C_j} > 0$, $j = 1, 2$. This important result is presented in the following proposition.

Proposition 2. *In each nation, the sulfur quota increases with the carbon quota.*

We now examine the conditions that determine the optimal choices in the previous stages of the various games, starting with the game in which the nations simultaneously and non-cooperatively choose carbon quotas and SRM levels.

³See derivations in Appendix A.4.

2.3.1 Game I: Simultaneous Choices of Carbon Quotas and SRM Levels

In the first stage, the government of nation j chooses non-negative $\{Q_{C_j}, M_j\}$ to maximize (2.8) subject to $Q_{S_j} = Q_{S_j}(Q_{C_j}; \theta_j)$, taking $\{Q_{C_{-j}}, M_{-j}\}$ as given. Assuming interior solutions, the set of first-order conditions are $j = (1, 2)$:

$$p_{C_j} = \frac{\partial H^T}{\partial Q_C}, \quad (2.11a)$$

$$-\frac{\partial H^T}{\partial M} = \frac{dK_j^M}{dM_j} + \frac{dH^D}{dM}. \quad (2.11b)$$

Condition (2.11a) reveals that the carbon quota in nation j should be set at the level that equates the national carbon permit price to the national marginal damage of global warming. Condition (2.11b) is similar in spirit, since the level of SRM that should be provided at nation j is the one under which the national marginal benefit from SRM provision — left side of (2.11b) — is equal to the national marginal cost — right side of (2.11b). The national marginal cost is the sum of the marginal cost of provision and the marginal damage caused by droughts in nation j .

The second partial derivatives of nation j 's payoff function are as follows:

$$\frac{\partial^2 v_j}{\partial Q_{C_j}^2} = \left(\frac{\partial P_{C_j}}{\partial Q_{C_j}} + \frac{\partial P_{C_j}}{\partial Q_{S_j}} \frac{\partial Q_{S_j}}{\partial Q_{C_j}} \right) - \frac{\partial^2 H^T}{\partial Q_C^2}, \quad (2.12a)$$

$$\frac{\partial^2 v_j}{\partial M_j^2} = -\frac{d^2 K_j^M}{dM_j^2} - \frac{\partial^2 H^T}{\partial M^2} - \frac{\partial^2 H^D}{\partial M^2}, \quad (2.12b)$$

$$\frac{\partial^2 v_j}{\partial Q_{C_j} \partial M_j} = -\frac{\partial^2 H^T}{\partial Q_C \partial M}, \quad (2.12c)$$

It is straightforward to show that our modeling assumptions imply that

$$\frac{\partial P_{C_j}}{\partial Q_{C_j}} + \frac{\partial P_{C_j}}{\partial Q_{S_j}} \frac{\partial Q_{S_j}}{\partial Q_{C_j}} < 0, \quad (2.13)$$

which implies that the direct effect of P_{C_j} on Q_{C_j} is greater than the indirect effect. Condition (2.13) implies that (2.12a) is negative. It then follows that the sufficient second order conditions are satisfied in each maximization problem because the Hessian matrix of second order terms is negative definite. Hence, the equilibrium for the first stage is unique.

2.3.2 Game II: Simultaneous Choices of Carbon Quotas and SRM Levels (Coordinated)

There exists an international agency simultaneously determining carbon pollution quotas and SRM levels for both nations in the first stage of the game. It takes into account the best response function of Q_{S_j} described by equation (2.10) and selects non-negative $\{Q_{C_1}, Q_{C_2}, M_1, M_2\}$ to maximize global indirect utility $V = v_1 + v_2$, where v_1 and v_2 correspond to function (2.8) by setting $j = 1, 2$, respectively.

Assuming interior solutions, the set of first-order conditions are as follows ($j = 1, 2$):

$$P_{C_j} - 2 \frac{\partial H^T}{\partial Q_C} = 0, \quad (2.14a)$$

$$\frac{dK_j^M}{dM_j} + 2 \left(\frac{\partial H^T}{\partial M} + \frac{dH^T}{dM} \right) = 0, \quad (2.14b)$$

Condition (2.14a) tells us that the amount of carbon quotas in nation j is chosen to equate the national carbon permit price to the social marginal damage of global warming. Condition (2.14b) means the similar: nation j should implement SRM at a level that equalizes the domestic marginal cost of SRM to the social marginal damage of droughts.

The second-order conditions are satisfied given our assumptions and therefore, there exists a unique solution to the international agency's maximization problem.

2.3.3 Game III: Simultaneous Choices of Carbon Quotas

The two nations make their own decisions on carbon quotas simultaneously before those on SRM levels. That is, in the second stage, the government of nation j chooses non-negative M_j to maximize its indirect utility function (2.8), subject to (2.10) and taking M_{-j} as given. Assuming interior solutions, the first-order condition is the same as equation (2.11b) in Game I (2.3.1). The second-order conditions are also satisfied under our assumptions. Then we can define $M_j(Q_C)$ implicitly from condition (2.11b) by differentiating the equation with respect to Q_C , which yields the slope of the best response function of M_j with respect to Q_C ($j = 1, 2$):

$$\frac{\partial M_j}{\partial Q_C} = - \frac{\frac{\partial^2 H^T}{\partial M \partial Q_C} \frac{d^2 K_j^M}{dM_j^2}}{\frac{d^2 K_1^M}{dM_1^2} \frac{d^2 K_2^M}{dM_2^2} + \left(\frac{d^2 K_1^M}{dM_1^2} + \frac{d^2 K_2^M}{dM_2^2} \right) \left(\frac{\partial H^T}{\partial M^2} + \frac{d^2 H^D}{dM^2} \right)} \quad (2.15)$$

Given our assumptions, we can easily get

$$\frac{\partial M_j}{\partial Q_C} > 0, \quad \forall j = 1, 2 \quad (2.16)$$

In the first stage, government j maximizes national indirect utility function (2.8) by selecting Q_{C_j} , subject to (2.10) and (2.15), taking $Q_{C_{-j}}$ as given. This yields the first-order condition for an interior solution as

$$P_{C_j} - \frac{\partial H^T}{\partial Q_C} - \left(\frac{\partial H^T}{\partial M} + \frac{dH^T}{dM} \right) \frac{dM_{-j}}{dQ_C} = 0 \quad (2.17)$$

Condition (2.17) demonstrates the tangency condition of how to determine the amount of carbon permits in one nation: equating the slope of iso-utility curve,

$$\left(P_{C_j} - \frac{\partial H^T}{\partial Q_C} \right) / \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right)$$

with the slope of best response function of the other nation, dM_{-j}/dQ_C .

The corresponding second-order condition is

$$\begin{aligned} \frac{\partial^2 v_j}{\partial Q_{C_j}^2} &= \frac{\partial P_{C_j}}{\partial Q_{C_j}} + \frac{\partial P_{C_j}}{\partial Q_{S_j}} \frac{\partial Q_{S_j}}{\partial Q_{C_j}} - \left(\frac{\partial^2 H^T}{\partial Q_C^2} + \frac{\partial^2 H^T}{\partial Q_C \partial M} \frac{\partial M}{\partial Q_C} \right) \\ &\quad - \frac{\partial M_{-j}}{\partial Q_C} \left[\frac{\partial M}{\partial Q_C} \left(\frac{\partial^2 H^T}{\partial M^2} + \frac{d^2 H^D}{dM^2} \right) + \frac{\partial^2 H^T}{\partial Q_C \partial M} \right] \end{aligned}$$

Assume that

$$\left(\frac{\partial^2 H^T}{\partial Q_C^2} + \frac{\partial^2 H^T}{\partial Q_C \partial M} \frac{\partial M}{\partial Q_C} \right) + \frac{\partial M_{-j}}{\partial Q_C} \left[\frac{\partial M}{\partial Q_C} \left(\frac{\partial^2 H^T}{\partial M^2} + \frac{d^2 H^D}{dM^2} \right) + \frac{\partial^2 H^T}{\partial Q_C \partial M} \right] > 0$$

then the second-order condition is satisfied. Hence, the solution to the government's maximization problem is unique.

2.3.4 Game IV: Simultaneous Choices of SRM levels

Now, the two nations decide their own SRM levels simultaneously before carbon permits levels. That is, in the second stage, government j selects non-negative Q_{C_j} to maximize its indirect utility function (2.8), subject to (2.10) and taking $\{Q_{C_{-j}}, M_j, M_{-j}\}$ as given. The first-order condition is the same as equation (2.11a) in the uncoordinated simultaneous game. Satisfaction of the second-order condition enables us to implicitly define $Q_{C_j}(M)$ from (2.11a) by differentiating both sides with

respect to M . We get the best response function of Q_{C_j} with respect to M ($j = 1, 2$):

$$\begin{aligned} \frac{\partial Q_{C_j}}{\partial M} = & \left[\left(\frac{\partial P_{C_1}}{\partial Q_{C_1}} + \frac{\partial P_{C_1}}{\partial Q_{S_1}} \frac{\partial Q_{S_1}}{\partial Q_{C_1}} \right) \left(\frac{\partial P_{C_2}}{\partial Q_{C_2}} + \frac{\partial P_{C_2}}{\partial Q_{S_2}} \frac{\partial Q_{S_2}}{\partial Q_{C_2}} \right) \right. \\ & \left. - \frac{\partial^2 H^T}{\partial Q_C^2} \left(\frac{\partial P_{C_1}}{\partial Q_{C_1}} + \frac{\partial P_{C_1}}{\partial Q_{S_1}} \frac{\partial Q_{S_1}}{\partial Q_{C_1}} + \frac{\partial P_{C_2}}{\partial Q_{C_2}} + \frac{\partial P_{C_2}}{\partial Q_{S_2}} \frac{\partial Q_{S_2}}{\partial Q_{C_2}} \right) \right] \\ & / \left[\frac{\partial^2 H^T}{\partial Q_C \partial M} \left(\frac{\partial P_{C_j}}{\partial Q_{C_j}} + \frac{\partial P_{C_j}}{\partial Q_{S_j}} \frac{\partial Q_{S_j}}{\partial Q_{C_j}} \right) \right] \end{aligned} \quad (2.18)$$

Given our assumptions, we can easily verify that

$$\frac{\partial Q_{C_j}}{\partial M} > 0, \quad \forall j = 1, 2 \quad (2.19)$$

Summarizing our findings about the relationship between the level of SRM and carbon quotas from (2.16) and (2.19), we reach the following proposition.

Proposition 3. *In sequential games, if both nations' amounts of carbon quotas are decided before their SRM levels, then the level of SRM in each nation increases in the global amount of carbon quotas. Conversely, if the nations' amounts of carbon quotas are chosen first, then the level of SRM in each country increases in the global amount of carbon quotas.*

In the first stage, each national government determines its level of SRM implementation to maximize its indirect utility, subject to (2.11a) and (2.18), and taking the other nation's choice as given. Assuming interior solutions, the first-order condition is: ($j = 1, 2$)

$$\frac{dK_j^M}{dM_j} + \frac{\partial H^T}{\partial M} + \frac{dH^T}{dM} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C-j}}{dM} = 0, \quad (2.20)$$

Just like equation (2.17) of game III, equation (2.20) also represents a tangency condition for deciding the level of SRM in each nation: the slope of iso-utility curve

of nation j , $-(dK_j^M/dM_j + \partial H^T/\partial M + dH^T/dM)$ is set equal to that of the best response function of nation $-j$, $\frac{\partial H^T}{\partial Q_C} \frac{dQ_{C-j}}{dM}$.

Meanwhile, the second-order condition is:

$$\begin{aligned} \frac{\partial^2 v_j}{\partial M_j^2} = & -\frac{d^2 K_j^M}{dM_j^2} - \frac{d^2 H^D}{dM^2} - \frac{\partial^2 H^T}{\partial M^2} - \frac{\partial Q_{C-j}}{\partial M} \frac{\partial^2 H^T}{\partial Q_C \partial M} \\ & - \frac{\partial Q_C}{\partial M} \left(\frac{\partial Q_{C-j}}{\partial M} \frac{\partial^2 H^T}{\partial Q_C^2} + \frac{\partial^2 H^T}{\partial M \partial Q_C} \right) \end{aligned}$$

Assume that

$$\frac{d^2 H^D}{dM^2} + \frac{\partial^2 H^T}{\partial M^2} + \frac{\partial Q_{C-j}}{\partial M} \frac{\partial^2 H^T}{\partial Q_C \partial M} + \frac{\partial Q_C}{\partial M} \left(\frac{\partial Q_{C-j}}{\partial M} \frac{\partial^2 H^T}{\partial Q_C^2} + \frac{\partial^2 H^T}{\partial M \partial Q_C} \right) > 0$$

then the second-order condition is satisfied, which ensures a unique solution to the maximization problem.

2.3.5 Game V: National Leadership in Carbon Quotas

Compared with game III (2.3.3), now one nation 1 acts strategically by moving first in deciding its national carbon quota. The behavior of both nations in the last two stages is the same as in game III. In the second stage, nation 2 determines Q_{C_2} by taking Q_{C_1} as given and taking into account the last two stages' best response functions. The first- and second-order conditions are the same as in the first stage of game III. Then we can implicitly define $Q_{C_2}(Q_{C_1})$ from condition (2.17):

$$\frac{\partial Q_{C_2}}{\partial Q_{C_1}} = \left(\frac{\partial P_{C_2}}{\partial Q_{C_2}} + \frac{\partial P_{C_2}}{\partial Q_{S_2}} \frac{\partial Q_{S_2}}{\partial Q_{C_2}} - \frac{\partial^2 v_2}{\partial Q_{C_2}^2} \right) / \left(\frac{\partial^2 v_2}{\partial Q_{C_2}^2} \right) \quad (2.21)$$

By (A.2), we obtain:

$$\frac{\partial Q_{C_2}}{\partial Q_{C_1}} < 0 \quad (2.22)$$

In the first stage, nation 1 takes into account the reactions in all later stages and chooses its amount of carbon quotas to maximize its national indirect utility. The first-order condition for an interior solution is:

$$P_{C_1} - \left[\frac{\partial H^T}{\partial Q_C} + \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \right] \left(1 + \frac{\partial Q_{C_2}}{\partial Q_{C_1}} \right) = 0 \quad (2.23)$$

Condition (2.23) is again a tangency condition where the slope of nation 1's iso-utility curve, $P_{C_1} / \left[\frac{\partial H^T}{\partial Q_C} + \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \right] - 1$ equals the slope of nation 2's best response function, $\partial Q_{C_2} / \partial Q_{C_1}$.

Moreover, we can prove that the second-order condition is satisfied given our assumptions. Hence, the maximization problem has a unique solution.

2.3.6 Game VI: National Leadership in SRM Levels

Compared with game IV (2.3.4), now nation 1 acts strategically by moving first in deciding its national SRM level. The behavior of both nations in the last two stages is the same as in game IV. In the second stage, nation 2 chooses M_2 to maximize its indirect utility, subject to (2.11a) and (2.18) and considering M_1 as given. After checking the first- and second-order conditions, we use implicit function theorem to define $M_2(M_1)$ from condition (2.20):

$$\frac{\partial M_2}{\partial M_1} = - \left(\frac{d^2 K_2^M}{dM_2^2} + \frac{\partial^2 v_1}{\partial M_1^2} \right) / \left(\frac{\partial^2 v_2}{\partial M_1^2} \right) \quad (2.24)$$

Given our assumptions, we have:

$$\frac{\partial M_2}{\partial M_1} < 0 \quad (2.25)$$

In the first stage, nation 1 determines M_1 to maximize its indirect utility and takes into account all the reactions in later stages. This results in the first-order condition

for an interior solution:

$$\left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_2}}{dM} \right) \left(1 + \frac{dM_2}{dM_1} \right) + \frac{dK_1^M}{dM_1} = 0 \quad (2.26)$$

Condition (2.26) is also a tangency condition for determining M_1 : equating the slope of nation 1's iso-utility curve,

$$-\frac{dK_1^M}{dM_1} / \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_2}}{dM} \right) - 1$$

with the slope of nation 2's best response function, dM_2/dM_1 .

We have checked that the second-order condition is satisfied under our assumptions. Hence, there exists a unique solution to the maximization problem.

2.4 *First-mover Advantage*

Since we have considered strategic movements in games V (2.3.5) and VI (2.3.6), we examine if there exists a first-mover advantage in deciding the national carbon quota level or the national SRM level in this section. By similar derivation as above, we can get

$$\frac{\partial Q_{C_1}}{\partial Q_{C_2}} < 0, \quad (2.27)$$

$$\frac{\partial M_1}{\partial M_2} < 0, \quad (2.28)$$

from (2.22), (2.25), (2.27) and (2.28), we conclude that Q_{C_1} and Q_{C_2} , M_1 and M_2 , are two pairs of strategic substitutes. Meanwhile, we can see that they are also two pairs of substitutes because v_j decreases in both Q_{C-j} and M_{-j} . Then according to Varian^[7], we have the following proposition.

Proposition 4. *There exist first-mover advantages in terms of choices of both carbon quotas and SRM levels.*

Hence, nations will find it desirable to commit to either SRM or carbon dioxide mitigation.

CHAPTER III

EXAMPLE

In this section, we assign specific functional forms to the utility, cost and harm functions. The equilibrium results verify the existence of first-mover advantage in terms of carbon and SRM policies. Moreover, we show that for all games, if a nation is more sensitive to acid rain damage, then it will issue less carbon quotas, implement less SRM and enjoy lower utility. The cross effects, i.e. impacts of the other nation's sensitivity to acid rain damage on a nation's indirect utility, have all results in the opposite direction. Hence, the knowledge of θ_1 and θ_2 will enable us to make some predictions about their movements. This also demonstrates that policies on sulfur are linked to those on carbon and therefore on SRM not only through energy production, but also through θ 's. In addition, we compare national payoffs and environmental damages in different games so as to predict which one would be the relevant Nash equilibrium in reality.

Suppose that

$$\begin{aligned} u_j &\equiv x_j + e_j(1 - e_j/2), & K_j^E &\equiv E_j^2/2, & K_j^C &\equiv R_{C_j}^2/2, \\ K_j^S &\equiv R_{S_j}^2/2, & K_j^M &\equiv M_j^2/2, & H^T &\equiv (C - M)^2/2, \\ H^D &\equiv M^2/2. & H_j^A &\equiv \theta_j S_j^2/2 & \text{and } \bar{x}_j &= 0, \forall j = 1, 2. \end{aligned}$$

Solving consumer j 's and producer j 's maximization problems, the general equilibrium results in nation j are as follows:

$$\begin{aligned}
e_j = E_j &= \frac{1}{4} (1 + Q_{C_j} + Q_{S_j}) \\
R_{C_j} &= \frac{1}{4} (1 - 3Q_{C_j} + Q_{S_j}) \\
R_{S_j} &= \frac{1}{4} (1 + Q_{C_j} - 3Q_{S_j}) \\
P_{e_j} &= \frac{1}{4} (3 - Q_{C_j} - Q_{S_j}) \\
P_{C_j} &= \frac{1}{4} (1 - 3Q_{C_j} + Q_{S_j}) \\
P_{S_j} &= \frac{1}{4} (1 + Q_{C_j} - 3Q_{S_j}) \\
\forall j &= 1, 2
\end{aligned}$$

Plugging those functions into equation (2.8), we obtain the indirect utility function of nation j :

$$v_j = \frac{1}{8} \left[1 - 4M_j^2 - 4M^2 - 4(Q_C - M)^2 - 3Q_{C_j}^2 + 2Q_{C_j}Q_{S_j} + 2(Q_{C_j} + Q_{S_j}) - (3 + 4\theta_j)Q_{S_j}^2 \right] \quad (3.1)$$

Now, we solve the governments' maximization problems in different games using

function (3.1). The Nash equilibria are as follows:

$$\begin{aligned}
Q_{C_j}^I &= \frac{10 + 7\theta_j + 18\theta_{-j} + 15\theta_j\theta_{-j}}{56 + 81(\theta_j + \theta_{-j}) + 117\theta_j\theta_{-j}} \\
Q_{S_j}^I &= \frac{22 + 33\theta_{-j}}{56 + 81(\theta_j + \theta_{-j}) + 117\theta_j\theta_{-j}} \\
M_j^I &= \frac{4 + 5(\theta_j + \theta_{-j}) + 6\theta_j\theta_{-j}}{56 + 81(\theta_j + \theta_{-j}) + 117\theta_j\theta_{-j}} \\
Q_{C_j}^{II} &= \frac{18 + 8\theta_j + 37\theta_{-j} + 27\theta_j\theta_{-j}}{156 + 224(\theta_j + \theta_{-j}) + 321\theta_j\theta_{-j}} \\
Q_{S_j}^{II} &= \frac{58 + 87\theta_{-j}}{156 + 224(\theta_j + \theta_{-j}) + 321\theta_j\theta_{-j}} \\
M_j^{II} &= \frac{8 + 10(\theta_j + \theta_{-j}) + 12\theta_j\theta_{-j}}{156 + 224(\theta_j + \theta_{-j}) + 321\theta_j\theta_{-j}} \\
Q_{C_j}^{III} &= \frac{50 + 36\theta_j + 89\theta_{-j} + 75\theta_j\theta_{-j}}{268 + 388(\theta_j + \theta_{-j}) + 561\theta_j\theta_{-j}} \\
Q_{S_j}^{III} &= \frac{53(\theta_j + \theta_{-j})}{268 + 388(\theta_j + \theta_{-j}) + 561\theta_j\theta_{-j}} \\
M_j^{III} &= \frac{20 + 25(\theta_j + \theta_{-j}) + 30\theta_j\theta_{-j}}{268 + 388(\theta_j + \theta_{-j}) + 561\theta_j\theta_{-j}} \\
Q_{C_j}^{IV} &= \frac{136 + 284\theta_j + 448\theta_{-j} + 976\theta_j\theta_{-j} + 127\theta_j^2 + 363\theta_{-j}^2 + 477\theta_j^2\theta_{-j} + 816\theta_j\theta_{-j}^2 + 423\theta_j^2\theta_{-j}^2}{848 + 2444(\theta_j + \theta_{-j}) + 7038\theta_j\theta_{-j} + 1761(\theta_j^2 + \theta_{-j}^2) + 5067(\theta_j^2\theta_{-j} + \theta_j\theta_{-j}^2) + 3645\theta_j^2\theta_{-j}^2} \\
Q_{S_j}^{IV} &= \frac{(2 + 3\theta_{-j})[164 + 236(\theta_j + \theta_{-j}) + 339\theta_j\theta_{-j}]}{848 + 2444(\theta_j + \theta_{-j}) + 7038\theta_j\theta_{-j} + 1761(\theta_j^2 + \theta_{-j}^2) + 5067(\theta_j^2\theta_{-j} + \theta_j\theta_{-j}^2) + 3645\theta_j^2\theta_{-j}^2} \\
M_j^{IV} &= \frac{40 + 102\theta_j + 114\theta_{-j} + 289\theta_j\theta_{-j} + 65\theta_j^2 + 80\theta_{-j}^2 + 183\theta_j^2\theta_{-j} + 201\theta_j\theta_{-j}^2 + 126\theta_j^2\theta_{-j}^2}{848 + 2444(\theta_j + \theta_{-j}) + 7038\theta_j\theta_{-j} + 1761(\theta_j^2 + \theta_{-j}^2) + 5067(\theta_j^2\theta_{-j} + \theta_j\theta_{-j}^2) + 3645\theta_j^2\theta_{-j}^2} \\
Q_{C_1}^V &= \frac{6364 + 5664\theta_1 + 18854\theta_2 + 17104\theta_1\theta_2 + 14011\theta_2^2 + 12961\theta_1\theta_2^2}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2} \\
Q_{C_2}^V &= \frac{2836 + 5746\theta_2 + 5836\theta_1 + 13071\theta_1\theta_2 + 2364\theta_2^2 + 6689\theta_1\theta_2^2}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2} \\
Q_{S_1}^V &= \frac{9164 + 26554\theta_2 + 19261\theta_2^2}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2} \\
Q_{S_2}^V &= \frac{7988 + 12276\theta_1 + 11534\theta_2 + 17693\theta_1\theta_2}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2} \\
M_1^V &= \frac{5(92 + 131\theta_2)[4 + 5(\theta_1 + \theta_2) + 6\theta_1\theta_2]}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2} \\
M_2^V &= \frac{5(92 + 131\theta_2)[4 + 5(\theta_1 + \theta_2) + 6\theta_1\theta_2]}{21128 + 30992\theta_1 + 60808\theta_2 + 89112\theta_1\theta_2 + 43772\theta_2^2 + 64083\theta_1\theta_2^2}
\end{aligned}$$

$$Q_{C_1}^{\text{VI}} = F_1/F$$

$$Q_{C_2}^{\text{VI}} = F_2/F$$

$$Q_{S_1}^{\text{VI}} = F_3/F$$

$$Q_{S_2}^{\text{VI}} = F_4/F$$

$$M_1^{\text{VI}} = F_5/F$$

$$M_2^{\text{VI}} = F_6/F$$

where $Q_{C_j}^i, Q_{S_j}^i, M_j^i$, $i = \text{I, II, } \dots, \text{VI}$, $j = 1, 2$ denotes the levels of carbon quotas, sulfur quotas and SRM of nation j in game i , and

$$\begin{aligned} F = & 380480 + 2193536\theta_1 + 2190144\theta_2 + 12621200\theta_1\theta_2 + 4742440\theta_1^2 + 4727576\theta_2^2 \\ & + 27275520\theta_1^2\theta_2 + 27232116\theta_1\theta_2^2 + 58825956\theta_1^2\theta_2^2 + 4557108\theta_1^3 + 4535400\theta_2^3 \\ & + 26198480\theta_1^3\theta_2 + 26113988\theta_1\theta_2^3 + 56479077\theta_1^3\theta_2^2 + 56386602\theta_1^2\theta_2^3 + 54114048\theta_1^3\theta_2^3 \\ & + 1642181\theta_1^4 + 1631615\theta_2^4 + 9436776\theta_1^4\theta_2 + 9390525\theta_1\theta_2^4 + 20335320\theta_1^4\theta_2^2 \\ & + 20267847\theta_1^2\theta_2^4 + 19475532\theta_1^4\theta_2^3 + 19442727\theta_1^3\theta_2^4 + 6994431\theta_1^4\theta_2^4 \\ F_1 = & 59680 + 296208\theta_1 + 368640\theta_2 + 1847624\theta_1\theta_2 + 536916\theta_1^2 + 849844\theta_2^2 \\ & + 3394698\theta_1^2\theta_2 + 4295218\theta_1\theta_2^2 + 7981832\theta_1^2\theta_2^2 + 416470\theta_1^3 + 867126\theta_2^3 \\ & + 2685977\theta_1^3\theta_2 + 4414401\theta_1\theta_2^3 + 6418320\theta_1^3\theta_2^2 + 8282796\theta_1^2\theta_2^3 + 6750099\theta_1^3\theta_2^3 \\ & + 114227\theta_1^4 + 330565\theta_2^4 + 760452\theta_1^4\theta_2 + 1693509\theta_1\theta_2^4 + 1862532\theta_1^4\theta_2^2 \\ & + 3203973\theta_1^2\theta_2^4 + 1997784\theta_1^4\theta_2^3 + 2640654\theta_1^3\theta_2^4 + 794205\theta_1^4\theta_2^4 \end{aligned}$$

$$\begin{aligned}
F_2 &= 59680 + 369568\theta_1 + 295280\theta_2 + 1846904\theta_1\theta_2 + 854060\theta_1^2 + 533420\theta_2^2 \\
&\quad + 4304800\theta_1^2\theta_2 + 3383016\theta_1\theta_2^2 + 7977241\theta_1^2\theta_2^2 + 873504\theta_1^3 + 412192\theta_2^3 \\
&\quad + 4435442\theta_1^3\theta_2 + 2667996\theta_1\theta_2^3 + 8300595\theta_1^3\theta_2^2 + 6396060\theta_1^2\theta_2^3 + 6746850\theta_1^3\theta_2^3 \\
&\quad + 333778\theta_1^4 + 112545\theta_2^4 + 1705779\theta_1^4\theta_2 + 752643\theta_1\theta_2^4 + 20335320\theta_1^4\theta_2^2 \\
&\quad + 1850481\theta_1^2\theta_2^4 + 2646837\theta_1^4\theta_2^3 + 1991601\theta_1^3\theta_2^4 + 794205\theta_1^4\theta_2^4 \\
F_3 &= (2 + 3\theta_2)(73360 + 317144\theta_1 + 316424\theta_2 + 1367136\theta_1\theta_2 + 457034\theta_1^2 + 454934\theta_2^2 \\
&\quad + 1969016\theta_1^2\theta_2 + 1964425\theta_1\theta_2^2 + 2827602\theta_1^2\theta_2^2 + 219551\theta_1^3 + 218020\theta_2^3 \\
&\quad + 945327\theta_1^3\theta_2 + 940866\theta_1\theta_2^3 + 1356741\theta_1^3\theta_2^2 + 1353492\theta_1^2\theta_2^3 + 649053\theta_1^3\theta_2^3) \\
F_4 &= (2 + 3\theta_1)(73360 + 317144\theta_1 + 316424\theta_2 + 1367136\theta_1\theta_2 + 457034\theta_1^2 + 454934\theta_2^2 \\
&\quad + 1969016\theta_1^2\theta_2 + 1964425\theta_1\theta_2^2 + 2827602\theta_1^2\theta_2^2 + 219551\theta_1^3 + 218020\theta_2^3 \\
&\quad + 945327\theta_1^3\theta_2 + 940866\theta_1\theta_2^3 + 1356741\theta_1^3\theta_2^2 + 1353492\theta_1^2\theta_2^3 + 649053\theta_1^3\theta_2^3) \\
F_5 &= [16 + 23(\theta_1 + \theta_2) + 33\theta_1\theta_2^2](40 + 102\theta_1 + 114\theta_2 + 289\theta_1\theta_2 + 65\theta_1^2 + 80\theta_2^2 \\
&\quad + 183\theta_1^2\theta_2 + 201\theta_1\theta_2^2 + 126\theta_1^2\theta_2^2) \\
F_6 &= [4 + 5(\theta_1 + \theta_2) + 6\theta_1\theta_2](5520 + 24456\theta_1 + 23352\theta_2 + 103460\theta_1\theta_2 + 36096\theta_1^2 \\
&\quad + 32916\theta_2^2 + 152699\theta_1^2\theta_2 + 145837\theta_1\theta_2^2 + 215244\theta_1^2\theta_2^2 + 17749\theta_1^3 + 15459\theta_2^3 \\
&\quad + 75081\theta_1^3\theta_2 + 68496\theta_1\theta_2^3 + 105831\theta_1^3\theta_2^2 + 101097\theta_1^2\theta_2^3 + 49707\theta_1^3\theta_2^3)
\end{aligned}$$

We have checked that all of those solutions are interior and the corresponding prices and levels of pollution reduction are all positive. This indicates that in all games, carbon mitigation and SRM are not perfect substitutes. Governments' optimal choices always consist of a portfolio of the two instruments. Substituting those results into function (3.1), we can obtain nation j 's payoff in game i , denoted by v_j^i , where

$i = \text{I, II}, \dots, \text{VI}$ and $j = 1, 2$. Assume in the sequel that nation 1 is the leader in games V and VI.

3.1 *First-mover Advantage*

To examine whether quantity leadership leads to higher national payoffs, we compare nation 1's payoffs in games where it is the leader in making environmental policies with the games where no leadership exist and have:

$$v_1^{\text{V}} > v_1^{\text{III}} \text{ and } v_1^{\text{VI}} > v_1^{\text{IV}}$$

The result confirms the existence of first-mover advantages in both carbon mitigation and SRM decisions.

3.2 *Comparative Statics with respect to θ 's*

Next, we further study how the advantages are affected by the two nations' sensitivities to acid rain damages. We find that

$$\begin{aligned} \frac{\partial v_1^{\text{V}}}{\partial \theta_1} &< \frac{\partial v_1^{\text{III}}}{\partial \theta_1} < 0, & \frac{\partial v_1^{\text{V}}}{\partial \theta_2} &> \frac{\partial v_1^{\text{III}}}{\partial \theta_2} > 0, \\ \frac{\partial v_1^{\text{VI}}}{\partial \theta_1} &< \frac{\partial v_1^{\text{IV}}}{\partial \theta_1} < 0, & \frac{\partial v_1^{\text{VI}}}{\partial \theta_2} &> \frac{\partial v_2^{\text{IV}}}{\partial \theta_1} > 0. \end{aligned}$$

Hence, a nation is more desirable to commit on either carbon quotas or SRM implementation if it suffers less from acid rain damage. If the other nation suffers more, it will be more desirable to move first in choosing carbon quotas but not SRM levels.

Meanwhile, we check how the choices of carbon quotas and SRM levels are affected

by θ 's:

$$\begin{aligned}\frac{\partial Q_{C_j}^i}{\partial \theta_j} &< 0, & \frac{\partial Q_{C_j}^i}{\partial \theta_{-j}} &> 0, \\ \frac{\partial M_j^i}{\partial \theta_j} &< 0, & \frac{\partial M_j^i}{\partial \theta_{-j}} &> 0, \\ \forall i = \text{I, II}, \dots, \text{VI} \text{ and } \forall j = 1, 2.\end{aligned}$$

These results show that environmental policies on carbon mitigation and SRM implementation are correlated with those on sulfur reduction not only through the link in energy production, but also through national sufferings from acid rain damages.

3.3 *Rankings of Global and National Payoffs*

Considering the promising technology of SRM, what timing strategies will utility-maximizing nations take in making environmental policies? To explore the answer, we compare global and national payoffs of the six games. The results are in listed in Table (B4) in the Appendix.

We can see that the coordinated game yields the highest utilities for both the leader and the follower, and thereby the global one. However, as it would not be surprising to see that countries may fail to cooperate in reality, let's look at the comparisons among games I (2.3.1) and III (2.3.3) to VI (2.3.6).

We can observe that for all payoff comparisons, games I and III are strictly dominated by games IV and VI. Next, if the leader in deciding carbon quotas has large enough bargaining power, then game V is the potential equilibrium. If not, then since the follower loses too much in game V, it would not be the relevant equilibrium considering equity. Rather, game IV would be the potential one if the follower in

making SRM policy can bribe the leader or logrolling is possible. Otherwise, the equilibrium could only be game VI which is the second-best for both nations. These results demonstrate that nations would not like to determine mitigation levels first as long as international equity is taken into account. This is known by forward-looking governments and so, they would take strategic timing by choosing SRM levels first rather than follow the technological timing as claimed by all the previous economic literatures.

3.4 Rankings of Environmental Damages

We have also listed a ranking of the levels of environmental damages in Table (B4) in the Appendix. An interesting observation is that the coordinated game produces the least damages of acid rain and global warming, but not that of the drought. This is because the optimal policy takes into account both positive and negative externalities of SRM, and thereby the SRM level is not the lowest. On the other hand, acid rain or global warming is either pure local bad or pure public bad, and so their levels are set to the minimal when payoff is the highest in the coordinated game. Moreover, note that games where carbon amounts are determined before SRM levels (games III and V) generally yield higher damages of both acid rain and droughts, but lower damages of global warming than games where SRM levels are chosen first (games IV and VI). Hence, in terms of the environment, it depends on the different weights governments put on the three damages to determine which decision is the first, mitigation or SRM. If nations are more concerned with acid rain or drought,

then in general they will strategically choose SRM levels before carbon quotas, which is opposite to the timing assumptions in all current economic literatures.

CHAPTER IV

CONCLUSION

This paper represents an initial trial of economic papers on geoengineering to study timing effects of mitigation and SRM policies via a general equilibrium model with correlated pollutants. We have proved the existence of first-mover advantage in choosing carbon quotas and SRM levels as well as the positive quantity relationship among sulfur permits, carbon permits and SRM. Moreover, nations' sensitivities to acid rain damage play important roles in governments' environmental policies. We have also shown that the cases where SRM levels are chosen first cannot be neglected as they may yield higher global and national payoffs with less acid rain and droughts damages.

Future work may incorporate uncertainties and asymmetric information in national costs and damages of SRM into the model. Meanwhile, we can apply the correlate pollutants framework to examining governance issues on geoengineering, which has been widely called for research.^[1]

APPENDIX A

DERIVATIONS AND PROOFS

A.1 Derivation of Implicit Functions of E_j , R_{C_j} , R_{S_j} in terms of P_{e_j} , P_{C_j} , P_{S_j}

By implicit function theorem, we have:

$$E_j \equiv E_j(P_{e_j}, P_{C_j}, P_{S_j})$$

$$R_{C_j} \equiv R_{C_j}(P_{e_j}, P_{C_j}, P_{S_j})$$

and

$$R_{S_j} \equiv R_{S_j}(P_{e_j}, P_{C_j}, P_{S_j})$$

Plugging those relationships back into conditions (2.4) and differentiating each new equation with respect to P_{e_j} yields:

$$\begin{aligned} 1 - \frac{d^2 K_j^E}{dE_j^2} \frac{\partial E_j}{\partial P_{e_j}} &= 0 \quad \Rightarrow \quad \frac{\partial E_j}{\partial P_{e_j}} = 1 / \left(\frac{d^2 K_j^E}{dE_j^2} \right) \\ -\frac{d^2 K_j^C}{dR_{C_j}^2} \frac{\partial R_{C_j}}{\partial P_{e_j}} &= 0 \quad \Rightarrow \quad \frac{\partial R_{C_j}}{\partial P_{e_j}} = 0 \\ -\frac{d^2 K_j^S}{dR_{S_j}^2} \frac{\partial R_{S_j}}{\partial P_{e_j}} &= 0 \quad \Rightarrow \quad \frac{\partial R_{S_j}}{\partial P_{e_j}} = 0 \end{aligned}$$

Similarly, we can derive the expressions of $\frac{\partial E_j}{\partial P_{C_j}}$, $\frac{\partial R_{C_j}}{\partial P_{C_j}}$, $\frac{\partial R_{S_j}}{\partial P_{C_j}}$, $\frac{\partial E_j}{\partial P_{S_j}}$, $\frac{\partial R_{C_j}}{\partial P_{S_j}}$, $\frac{\partial R_{S_j}}{\partial P_{S_j}}$, and thereby obtain equations (2.5).

A.2 Derivation of Implicit Price Functions P_{e_j} , P_{C_j} , P_{S_j} in terms of Q_{C_j} , Q_{S_j}

Since $P_{e_j} \equiv P_{e_j}(Q_{C_j}, Q_{S_j})$, $P_{C_j} \equiv P_{C_j}(Q_{C_j}, Q_{S_j})$, and $P_{S_j} \equiv P_{S_j}(Q_{C_j}, Q_{S_j})$, differentiate both sides of equations (2.6) with respect to Q_{C_j} yields:

$$\begin{aligned} \left(\frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} \right) \frac{\partial P_{e_j}}{\partial Q_{C_j}} - \frac{\partial E_j}{\partial P_{C_j}} \frac{\partial P_{C_j}}{\partial Q_{C_j}} - \frac{\partial E_j}{\partial P_{S_j}} \frac{\partial P_{S_j}}{\partial Q_{C_j}} &= 0, \\ \frac{\partial E_j}{\partial P_{e_j}} \frac{\partial P_{e_j}}{\partial Q_{C_j}} + \left(\frac{\partial E_j}{\partial P_{C_j}} - \frac{dR_{C_j}}{dP_{C_j}} \right) \frac{\partial P_{C_j}}{\partial Q_{C_j}} + \frac{\partial E_j}{\partial P_{S_j}} \frac{\partial P_{S_j}}{\partial Q_{C_j}} &= 1, \\ \frac{\partial E_j}{\partial P_{e_j}} \frac{\partial P_{e_j}}{\partial Q_{C_j}} + \frac{\partial E_j}{\partial P_{C_j}} \frac{\partial P_{C_j}}{\partial Q_{C_j}} + \left(\frac{\partial E_j}{\partial P_{S_j}} - \frac{dR_{S_j}}{dP_{S_j}} \right) \frac{\partial P_{S_j}}{\partial Q_{C_j}} &= 0. \end{aligned}$$

Rewrite the equations into matrix forms:

$$\begin{pmatrix} \frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} & -\frac{\partial E_j}{\partial P_{C_j}} & -\frac{\partial E_j}{\partial P_{S_j}} \\ \frac{\partial E_j}{\partial P_{e_j}} & \frac{\partial E_j}{\partial P_{C_j}} - \frac{dR_{C_j}}{dP_{C_j}} & \frac{\partial E_j}{\partial P_{S_j}} \\ \frac{\partial E_j}{\partial P_{e_j}} & \frac{\partial E_j}{\partial P_{C_j}} & \frac{\partial E_j}{\partial P_{S_j}} - \frac{dR_{S_j}}{dP_{S_j}} \end{pmatrix} \begin{pmatrix} \frac{\partial P_{e_j}}{\partial Q_{C_j}} \\ \frac{\partial P_{C_j}}{\partial Q_{C_j}} \\ \frac{\partial P_{S_j}}{\partial Q_{C_j}} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

Let \mathbf{J} denote the coefficient matrix. Then

$$|\mathbf{J}| = \frac{dR_{C_j}}{dP_{C_j}} \left[2 \left(\frac{de_j}{dP_{e_j}} \right) \left(\frac{\partial E_j}{\partial P_{e_j}} \right) + \frac{dR_{C_j}}{dP_{C_j}} \left(\frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} \right) \right] < 0.$$

Meanwhile,

$$\begin{vmatrix} \frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} & -\frac{\partial E_j}{\partial P_{C_j}} \\ \frac{\partial E_j}{\partial P_{e_j}} & \frac{\partial E_j}{\partial P_{C_j}} - \frac{dR_{C_j}}{dP_{C_j}} \end{vmatrix} = \frac{de_j}{dP_{e_j}} \frac{\partial E_j}{\partial P_{C_j}} + \frac{dR_{C_j}}{dP_{C_j}} \left(\frac{\partial E_j}{\partial P_{e_j}} - \frac{de_j}{dP_{e_j}} \right) > 0$$

$$\text{and } \left| \frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} \right| < 0$$

Hence, \mathbf{J} is negative definite. By Crammer's Rule,

$$\begin{aligned} \frac{\partial P_{e_j}}{\partial Q_{C_j}} &= \frac{\begin{vmatrix} 0 & -\frac{\partial E_j}{\partial P_{C_j}} & -\frac{\partial E_j}{\partial P_{S_j}} \\ 1 & \frac{\partial E_j}{\partial P_{C_j}} - \frac{dR_{C_j}}{dP_{C_j}} & \frac{\partial E_j}{\partial P_{S_j}} \\ 0 & \frac{\partial E_j}{\partial P_{C_j}} & \frac{\partial E_j}{\partial P_{S_j}} - \frac{dR_{S_j}}{dP_{S_j}} \end{vmatrix}}{|\mathbf{J}|} = -f_j''(e_j) \left[2 \left(\frac{d^2 K_j^C}{dR_{C_j}^2} \right) + \frac{d^2 K_j^E}{dE_j^2} \right] / \left[2 \left(\frac{d^2 K_j^E}{dE_j^2} \right) \right] \\ \frac{\partial P_{C_j}}{\partial Q_{C_j}} &= \frac{\begin{vmatrix} \frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} & 0 & -\frac{\partial E_j}{\partial P_{S_j}} \\ \frac{\partial E_j}{\partial P_{e_j}} & 1 & \frac{\partial E_j}{\partial P_{S_j}} \\ \frac{\partial E_j}{\partial P_{e_j}} & 0 & \frac{\partial E_j}{\partial P_{S_j}} - \frac{dR_{S_j}}{dP_{S_j}} \end{vmatrix}}{|\mathbf{J}|} = \left(f_j''(e_j) - \frac{d^2 K_j^C}{dR_{C_j}^2} - \frac{d^2 K_j^E}{dE_j^2} \right) / 2 \\ \frac{\partial P_{S_j}}{\partial Q_{C_j}} &= \frac{\begin{vmatrix} \frac{de_j}{dP_{e_j}} - \frac{\partial E_j}{\partial P_{e_j}} & -\frac{\partial E_j}{\partial P_{C_j}} & 0 \\ \frac{\partial E_j}{\partial P_{e_j}} & \frac{\partial E_j}{\partial P_{S_j}} - \frac{dR_{C_j}}{dP_{C_j}} & 1 \\ \frac{\partial E_j}{\partial P_{e_j}} & \frac{\partial E_j}{\partial P_{C_j}} & 0 \end{vmatrix}}{|\mathbf{J}|} = \frac{d^2 K_j^C}{dR_{C_j}^2} \left(\frac{d^2 K_j^E}{dE_j^2} - 2f_j''(e_j) \right) / \left[2 \left(\frac{d^2 K_j^E}{dE_j^2} \right) \right] \end{aligned}$$

Similarly, we can obtain the expressions of $\frac{\partial P_{e_j}}{\partial Q_{S_j}}$, $\frac{\partial P_{C_j}}{\partial Q_{S_j}}$ and $\frac{\partial P_{S_j}}{\partial Q_{S_j}}$.

A.3 Proof of Proposition 1

Proof. We get signs of those partial derivatives directly from assumptions on concavity of the utility function and convexity of cost functions. \square

A.4 Derivation of the First-order Condition (2.9)

Substituting equations (2.7) into (2.6) yields:

$$e_j(p_{e_j}(Q_{C_j}, Q_{S_j})) = E_j(P_{e_j}(Q_{C_j}, Q_{S_j}), P_{C_j}(Q_{C_j}, Q_{S_j}), P_{S_j}(Q_{C_j}, Q_{S_j})) \quad (\text{A.1a})$$

$$E_j(P_{e_j}(Q_{C_j}, Q_{S_j}), P_{C_j}(Q_{C_j}, Q_{S_j}), P_{S_j}(Q_{C_j}, Q_{S_j})) - R_{C_j}(P_{C_j}(Q_{C_j}, Q_{S_j})) = Q_{C_j} \quad (\text{A.1b})$$

$$E_j(P_{e_j}(Q_{C_j}, Q_{S_j}), P_{C_j}(Q_{C_j}, Q_{S_j}), P_{S_j}(Q_{C_j}, Q_{S_j})) - R_{S_j}(P_{C_j}(Q_{C_j}, Q_{S_j})) = Q_{S_j} \quad (\text{A.1c})$$

Differentiate both sides of equations (A.1) with respect to Q_{S_j} :

$$\frac{\partial e_j}{\partial Q_{S_j}} = \frac{\partial E_j}{\partial Q_{S_j}} \quad (\text{A.2a})$$

$$\frac{\partial E_j}{\partial Q_{S_j}} = \frac{\partial R_{C_j}}{\partial Q_{S_j}} \quad (\text{A.2b})$$

$$\frac{\partial e_j}{\partial Q_{S_j}} = \frac{\partial R_{S_j}}{\partial Q_{S_j}} + 1 \quad (\text{A.2c})$$

Combining equations (A.2), (2.3) and (2.4), we have:

$$\begin{aligned} \frac{\partial v_j}{\partial Q_{S_j}} &= f'_j(e_j) \frac{\partial e_j}{\partial Q_{S_j}} - \frac{dK_j^E}{dE_j} \frac{\partial E_j}{\partial Q_{S_j}} \\ &\quad - \frac{dK_j^C}{dR_{C_j}} \frac{\partial R_{C_j}}{\partial Q_{S_j}} - \frac{dK_j^S}{dR_{S_j}} \frac{\partial R_{S_j}}{\partial Q_{S_j}} - \frac{\partial H_j^A}{\partial Q_{S_j}} \\ &= \left(P_{e_j} - \frac{dK_j^E}{dE_j} \right) \frac{\partial E_j}{\partial Q_{S_j}} - \frac{dK_j^C}{dR_{C_j}} \frac{\partial E_j}{\partial Q_{S_j}} \\ &\quad - \frac{dK_j^S}{dR_{S_j}} \left(\frac{\partial E_j}{\partial Q_{S_j}} - 1 \right) - \frac{\partial H_j^A}{\partial Q_{S_j}} \\ &= \frac{dK_j^S}{dR_{S_j}} - \frac{\partial H_j^A}{\partial Q_{S_j}} = P_{S_j} - \frac{\partial H_j^A}{\partial Q_{S_j}} = 0 \end{aligned}$$

Thus, $P_{S_j} = \frac{\partial H_j^A}{\partial Q_{S_j}}$.

APPENDIX B

TABLES

Table B1: Descriptions of the Games

Time	Descriptions
Simulations	The four choices, both nations' carbon quotas and SRM levels, are made simultaneously.
1) Uncoordinated	Carbon quotas and SRM levels are uncoordinated between the two nations, respectively.
2) Coordinated	Carbon quotas and SRM levels are coordinated between the two nations, respectively.
Sequential	
<i>No National Leadership</i>	
3) 1 st Stage: Carbon Quotas	Nations decide carbon quotas simultaneously in the 1 st stage and choose SRM levels simultaneously in the 2 nd stage.
4) 1 st Stage: SRM Levels	Nations choose SRM levels simultaneously in the 1 st stage and decide carbon quotas simultaneously in the 2 nd stage.
<i>National Leadership</i>	
5) 1 st Stage: Nation 1's Carbon Quotas	In the 1 st stage, nation 1 decides its carbon quota, followed by nation 2's carbon decision in the 2 nd stage. Both nations choose SRM levels simultaneously in the 3 rd stage.
6) 1 st Stage: Nation 1's SRM Level	In the 1 st stage, nation 1 chooses its SRM level, followed by nation 2's SRM choice in the 2 nd stage. Both nations decide carbon quotas simultaneously in the 3 rd stage.

Table B2: First-order Conditions of the Games

Timing	Q_{C_1}	Q_{C_2}
Simultaneous		
1) Uncoordinated	$P_{C_1} - \frac{\partial H^T}{\partial Q_C} = 0$	$P_{C_2} - \frac{\partial H^T}{\partial Q_C} = 0$
2) Coordinated	$P_{C_1} - 2 \left(\frac{\partial H^T}{\partial Q_C} \right) = 0$	$P_{C_2} - 2 \left(\frac{\partial H^T}{\partial Q_C} \right) = 0$
Sequential		
<i>No National Leadership</i>		
3) 1 st Stage: Carbon Quotas	$P_{C_1} - \frac{\partial H^T}{\partial Q_C} - \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \frac{dM_2}{dQ_C} = 0$	$P_{C_2} - \frac{\partial H^T}{\partial Q_C} - \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \frac{dM_1}{dQ_C} = 0$
4) 1 st Stage: SRM Levels	$P_{C_1} - \frac{\partial H^T}{\partial Q_C} = 0$	$P_{C_2} - \frac{\partial H^T}{\partial Q_C} = 0$
<i>National Leadership</i>		
5) 1 st Stage:		
Nation 1's Carbon Quotas	$P_{C_1} - \left[\frac{\partial H^T}{\partial Q_C} + \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \frac{dM_2}{dQ_C} \right] \left(1 + \frac{dQ_{C_2}}{dQ_{C_1}} \right) = 0$	$P_{C_2} - \frac{\partial H^T}{\partial Q_C} - \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) \frac{dM_1}{dQ_C} = 0$
6) 1 st Stage:		
Nation 1's SRM Level	$P_{C_1} - \frac{\partial H^T}{\partial Q_C} = 0$	$P_{C_2} - \frac{\partial H^T}{\partial Q_C} = 0$
Timing	M_1	M_2
Simultaneous		
1) Uncoordinated	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_1^M}{dM_1} = 0$	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_2^M}{dM_2} = 0$
2) Coordinated	$2 \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) + \frac{dK_1^M}{dM_1} = 0$	$2 \left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} \right) + \frac{dK_2^M}{dM_2} = 0$
Sequential		
<i>No National Leadership</i>		
3) 1 st Stage: Carbon Quotas	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_1^M}{dM_1} = 0$	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_2^M}{dM_2} = 0$
4) 1 st Stage: SRM Levels	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_1^M}{dM_1} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_2}}{dM} = 0$	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_2^M}{dM_2} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_1}}{dM} = 0$
<i>National Leadership</i>		
5) 1 st Stage:		
Nation 1's Carbon Quotas	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_1^M}{dM_1} = 0$	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_2^M}{dM_2} = 0$
6) 1 st Stage:		
Nation 1's SRM Level	$\left(\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_2}}{dM} \right) \left(1 + \frac{dM_2}{dM_1} \right) + \frac{dK_1^M}{dM_1} = 0$	$\frac{\partial H^T}{\partial M} + \frac{dH^D}{dM} + \frac{dK_2^M}{dM_2} + \frac{\partial H^T}{\partial Q_C} \frac{dQ_{C_1}}{dM} = 0$

Table B3: Slopes of Best Response Functions of Sequential Games without National Leadership

First Stage	Slopes of Best Response Functions
Carbon Quotas	$\frac{dQ_{C_1}}{dQ_{C_2}} = \left(\frac{\partial P_{C_1}}{\partial Q_{C_1}} + \frac{\partial P_{C_1}}{\partial Q_{S_1}} \frac{dQ_{S_1}}{dQ_{C_1}} - \frac{\partial^2 V_1}{\partial Q_{C_1}^2} \right) / \left(\frac{\partial^2 V_1}{\partial Q_{C_1}^2} \right) < 0$
	$\frac{dQ_{C_2}}{dQ_{C_1}} = \left(\frac{\partial P_{C_2}}{\partial Q_{C_2}} + \frac{\partial P_{C_2}}{\partial Q_{S_2}} \frac{dQ_{S_2}}{dQ_{C_2}} - \frac{\partial^2 V_2}{\partial Q_{C_2}^2} \right) / \left(\frac{\partial^2 V_2}{\partial Q_{C_2}^2} \right) < 0$
SRM Levels	$\frac{dM_1}{dM_2} = - \left(\frac{d^2 K_1^M}{dM_1^2} + \frac{\partial^2 V_2}{\partial M_2^2} \right) / \left(\frac{\partial^2 V_2}{\partial M_2^2} \right) < 0$
	$\frac{dM_2}{dM_1} = - \left(\frac{d^2 K_2^M}{dM_2^2} + \frac{\partial^2 V_1}{\partial M_1^2} \right) / \left(\frac{\partial^2 V_1}{\partial M_1^2} \right) < 0$

Table B4: Rankings of the Payoffs and Environmental Damages

Rankings	1	2	3	4	5	6
V	V	III	I	VI	IV	II
v_1	III	I	IV	VI	V	II
v_2	V	III	I	VI	IV	II
A_1	II	VI	IV	I	III	V
A_2	II	V	VI	IV	I	III
D	VI	IV	II	I	III	V
T	II	I	III	IV	V	VI

Note: V global welfare
 v_1 nation 1's payoff
 v_2 nation 2's payoff
 A_1 nation 1's acid rain level
 A_2 nation 2's acid rain level
 D global level of droughts
 T global level of global warming
"6" stands for the largest in the ranking

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